The TACOM-USU Intelligent Mobility Program

Kevin L. Moore
Center for Self-Organizing and Intelligent Systems
Utah State University 4160 Old Main Hill
Logan, UT 84322-4160, USA
moorek@ece.usu.ed

Grant Gerhart
US Army Tank-Automotive and Armaments Command
AMSTA-TR-R/263
Warren, MI 48397
gerhartg@tacom.army.mil

ABSTRACT

Over a six year period the US Army Tank-Automotive and Armaments Command's Intelligent Mobility Program sponsored research to develop and demonstrate enhanced mobility concepts for unmanned ground vehicles. In this paper we describe the Intelligent Mobility Program's research accomplishments achieved at Utah State University's (USU) Center for Self-Organizing and Intelligent Systems (CSIOS). The CSOIS program was based on USU's "smart wheel" technology, which enables design of an omni-directional vehicle (ODV). Through the course of the program, USU researchers built thirty robots using eight distinct ODV robot designs. These robots were also demonstrated in a number of application scenarios. The program has culminated in the actual fielding of the final robot developed, the ODIS-T2, which was designed for undervehicle inspection at security checkpoints. The design and deployment of these robots required research advances in mechanical and vetronics design, sensor integration, control engineering and intelligent behavior generation algorithms, system integration, and human interface. An overview of the USU-developed robotics technology is presented that details the technology development and technical accomplishments achieved by the TACOM-USU Intelligent Mobility Program, with a focus on the actual hardware produced.
Keywords: Mobile robotics, omni-directional drive, undervehicle inspection, ODIS.

1. TACOM-USU INTELLIGENT MOBILITY PROGRAM OVERVIEW

Beginning in FY98 and continuing through FY04, the Center for Self-Organizing and Intelligent Systems (CSOIS) at Utah State University (USU) was funded by the Office of the Secretary of Defense through the US Army Tank-Automotive and Armaments Command's (TACOM) Intelligent Mobility (IM) Program (under agreement No. DAAE07-98-3-0023) to develop a new generation of intelligent and highly-mobile robots. The long-range goal of the program was "… to develop and demonstrate enabling technologies that allow lightweight robotic and semiautonomous ground vehicles to achieve on-road and off-road mobility and survivability similar to current manned, wheeled, and tracked military vehicles, with a focus on small-scale to mid-scale vehicles…" The CSOIS program was based on USU's "smart wheel" technology, a mechatronic system that provides independent computer control of steering and drive in a single wheel assembly. Putting multiple smart wheels on a chassis gives a vehicle that is capable of (nearly) uncoupled translational and rotational motion. USU researchers built thirty robots using eight distinct designs. These robots, the T1, T2 (and the enhanced T2, theT2E), T3, T4, ODIS-I, ODIS-T (3 copies built), ODIS-S (2 copies built), and ODIS-T2 (20 copies built), were all based on the smart wheel mobility concept and included both electric and hydraulic drive robots, as well as robots exhibiting both three and six degrees of freedom and robots deploying a variety of payloads. USU efforts also included demonstration in a number of application scenarios and in the actual fielding of the final robot developed, the ODIS-T2, which was designed for undervehicle inspection at security checkpoints. Figure 1 shows the T1, T2, T3, and ODIS robots. Figure 2 shows the complete line of ODIS robots along with the T2e and T4 robots. In this paper we give an overview of the IM program, beginning with a summary of USU's smart wheel technology, continuing with a discussion of each robot and their associated technical accomplishments, and ending with a summary of the scholarly and educational impact of the program.

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14. ABSTRACT
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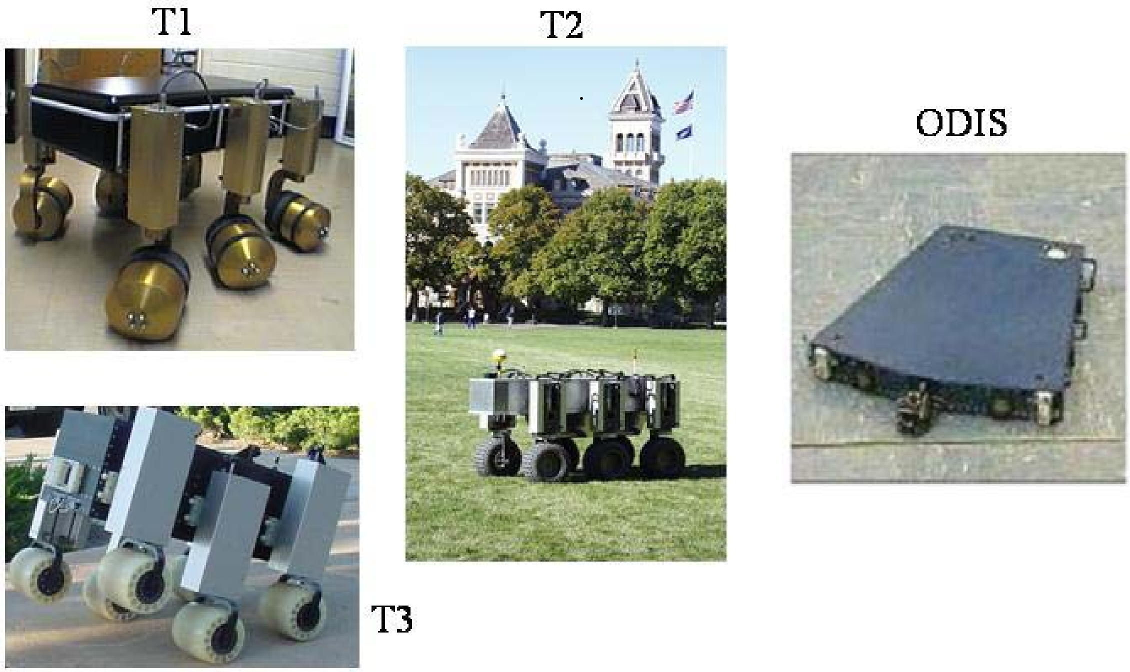
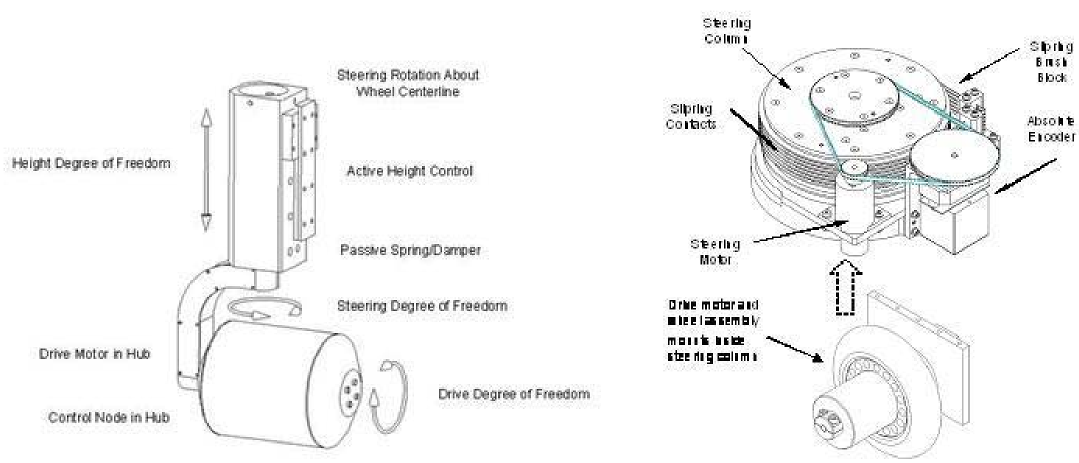


Figure 1: T1, T2, T3, and ODIS-I robots

Figure 2: T4, T2e, ODIS-I, ODIS-T, ODIS-S, and ODIS-T2 robots.

2. USU SMART WHEEL AND ODV PLATFORMS

We have previously noted that our perspective on developing effective robotic systems for UGV applications is that you must have a mobility capability to work with and you must have the proper mobility control to effectively utilize the mobility capability. For the robotic platforms developed at USU the core mobility capability is called the “smart wheel.” Figure 3 shows the smart wheel concepts used in the T-Series and ODIS robots. Using slip-rings, it is possible to achieve independent control over drive and steering motors and to obtain infinite rotation in the steering axis of the wheel. The actual implementation of the smart wheel concept has varied from vehicle-to-vehicle. For instance, in T1, each smart wheel has a drive motor, power, and a micro-controller, all in the wheel hub. This is combined with a separate steering motor to create a three degree-of-freedom mechanism. Infinite rotation in the steering degree-of-freedom is achieved through an innovative slip ring that allows data and, in the T2, T3, T4, and ODIS robots, power to pass from the chassis to the wheel without a wired connection. The T3 robot also includes actuation in the *z*-axis.



(a) (b)

Figure 3: Smart wheel designs – (a) T3 wheel concept; (b) ODIS-I smart wheel.

The USU concept for building mobile robots features multiple smart wheels attached to a chassis. The robotic platforms resulting from attaching multiple smart wheels to a chassis are called omni-directional vehicles, or ODV, because the resulting vehicle can drive a path with independent orientation and motion in the *X-Y* plane. This is different from a traditional Ackerman-steered vehicle or a tracked vehicle that must use skid-steering. In such vehicles orientation is constrained by the direction of travel. However, an ODV vehicle using USU's "smart wheels" has a much higher degree of mobility. This mobility has previously been described as being like a “hovercraft on wheels.” For the T1, T2, T4, and ODIS robots and like a “helicopter on wheels” for the T3 robot.

3. T-SERIES ROBOTS

3.1. The T1 and T2 ODV Vehicles

Figure 1 showed the T1, a 95 lb. ODV vehicle with six smart wheels. Because this vehicle was developed as prototype for the T2, its performance was not benchmarked and has always been considered “as-built.” T1 was built during the first year of the IM program, along with T2, which was design to demonstrate the scalability of the ODV concept. Figure 4 shows another view of the T2 robot. Its geometry and performance characteristics include:

- Size: 97" long x 40" wide x 44" high
- Weight (no payload): 1480 lb.
- Speed (flat and level surface): up to11.7 feet/sec (0-8 MPH)
- Uphill traction limited slope: 35° to 40° depending on soil traction assumptions
- Maximum slope stability limit: 57° aligned with the principle axis, 38° aligned with the minor axis
- Vehicle run time: 30 minutes based on 20 minutes of full speed hard level surface running plus 10 minutes of maximum torque running

Figure 4: The T2 ODV autonomous mobile robot.

3.2. The T3 ODV Vehicle

During the second year of the TACOM IM program CSOIS built the T3, an ODV robotic vehicle with six complete three degree-of-freedom smart wheels. The T3 is in the same weight and size class as the T1, with the following features:

- Top Speed: 10 mph
- Maximum Slope: 45°
- Maximum Weight: 100 lbs.
- Size: 20” wide x 26” long and 18” high
- Z-axis Travel: 7.5” stop to stop
- Z-axis Travel Rate: 2 inches/second
- Maximum Z-axis Force: 75 lb
- Maximum slope stability limit: 57° aligned with the principle axis, 38° aligned with the minor axis
- Vehicle run time: 30 minutes based on 20 minutes of full speed hard level surface running plus 10 minutes of maximum torque running

The key difference between the T3 and the earlier robots, T1 and T2, was the addition of z-axis capability, which provided an interesting new mobility capability, such as the ability to climb step-ups and curbs. Another new concept introduced in the T3 design was a modular “plug-and-play” approach to the wheel assembly and its connection to the vehicle chassis. This idea is shown in Figure 5. The basic concept is that wheels can be easily removed and replaced for repair as needed.

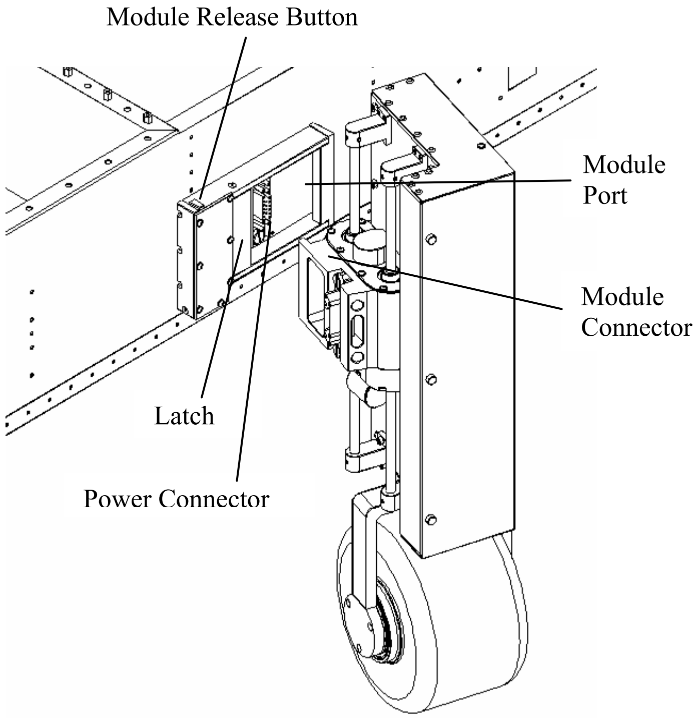


Figure 5: Modular wheel assembly attachment port.

4. ODIS SERIES ROBOTS

The T-series of robots were developed to demonstrate the feasibility and scalability of the ODV concept. The next step for CSOIS was to design a complete robotic system for a practical, real-world application. The resulting system, developed during the third year of the program, is called the Omni-Directional Inspection System (ODIS). ODIS is a man-portable physical security mobile robotic system that can be used for autonomous or semi-autonomous inspection under vehicles in a parking area. Customers for such a system include military police and other law enforcement entities interested in searching under vehicles for bombs or contraband.

ODIS-I, shown in Figure 7 carrying out an inspection task, is only 3.75 inches tall and has three wheels, each with the same ODV capability found in the T-series of robots. Using GPS, odometry, and on-board sensors, ODIS can navigate though a parking area either, a) going from stall to stall, inspecting any vehicles that it finds, or, b) going to a prescribed location and inspecting any vehicles it finds in that location. Once a vehicle is found to be in a parking stall some form of inspection may be carried out. After deciding to inspect a vehicle, ODIS characterizes the vehicle, finding bumper and tire locations, and then autonomously travels under the vehicle, sending streaming video back to the operator station for analysis.

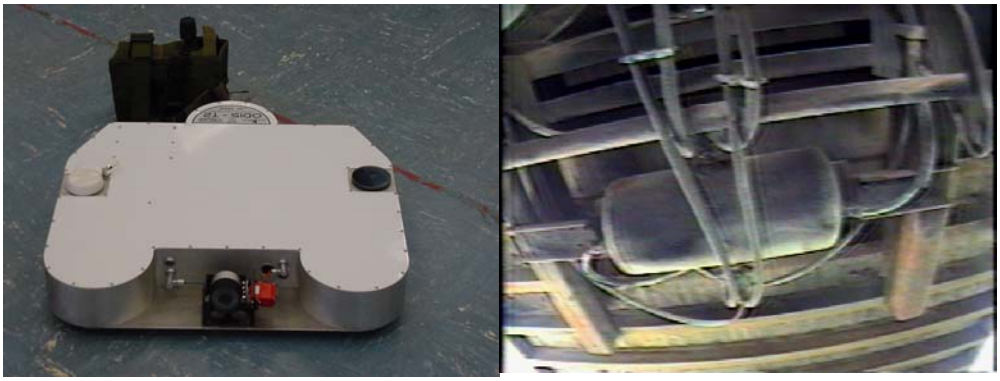
A second version of ODIS is the tele-operated **ODIS-T**, shown in Figure 7. ODIS-T was developed in response to the terrorist attacks on the World Trade Center and the Pentagon on September 11, 2001. The robot is intended to be driven by an operator and was designed to be able to deploy a number of mission sensors, including visual cameras, infrared cameras, chemical sniffers, and radiation detectors. Limited objective experiments of three ODIS-T robots being used by military police were carried out at Fort Leonard Wood in August 2002. The robots were found to be very effective when compared to the traditional “mirror-on-a-stick” method of under-vehicle inspection at security checkpoints. In particular, it has been found that ODV mobility is a very useful feature for under-vehicle inspection as the operator can move the robot in a natural way while focusing the camera on desired inspection points.

Figure 6: ODIS-I robot performing an inspection task.

Figure 7: ODIS-T robot.

The third version of ODIS, called the **ODIS-S**, was developed in the fourth and fifth year of the project, for a customer who wished to have the autonomy of ODIS-I with the improved wheel assembly of ODIS-T. ODIS-S, shown above in the lower right-hand corner of Figure 2, is a semi-autonomous robot that can be tele-operated via a simple physical joystick or through a virtual joystick on a PC-based OCU. It is semi-autonomous in the sense that the vehicle can have the ability to do localized area path planning and obstacle avoidance. Its mission capabilities will include a “sentry mode” function that will allow the robot to automatically inspect a car after being tele-operating into the cars vicinity. Software provided with the vehicle enables following behaviors that can be commanded through the SPAWAR MHRA system, including: GPS-based waypoint navigation; automatic under-car raster scan searches; automatic entry and exit from under the car from GPS specified positions; non-dynamic collision avoidance of static obstacles (by coming to a stop).

Finally, in years five and six of the program a fourth version of ODIS was designed, called the **ODIS-T2**, shown in Figure 9. The ODIS-T2 robot was designed as an improved ODIS-T robot for the specific application of military police and law enforcement checkpoint inspection. A novel feature of this effort, which took place during year six of the program, was a teaming with a manufacturer who carried out a complete design for manufacture and assembly (DFMA) assessment of the design as well as assembly instructions. Twenty copies of the ODIS-T2 robot were produced in an assembly-line fashion, with ten of these robots deployed in the Iraq theatre.



(a) ODIS-T2 robot. (b) Image obtained from ODIS-T2.

Figure 8: The ODIS-T2 robot.

5. Integrated Parking Security System

During the fourth year of the Intelligent Mobility program, CSOIS began development of a complete integrated parking area surveillance system. The concept is shown in Figure 9. The system will use one or more ODIS robots for performing fine resolution inspection and clandestine surveillance. In addition, a mid-sized mobile robot, called the T4, will be used as a "marsupial mothership" for one of the ODIS vehicles and will also perform coarse resolution inspection (such as license plate recognition), parking area monitoring and security, and general surveillance. T4 enhances the mobility of ODIS. These robots will be deployed to work together, both autonomously and semi-autonomously, to provide a variety of security functions for parking areas.

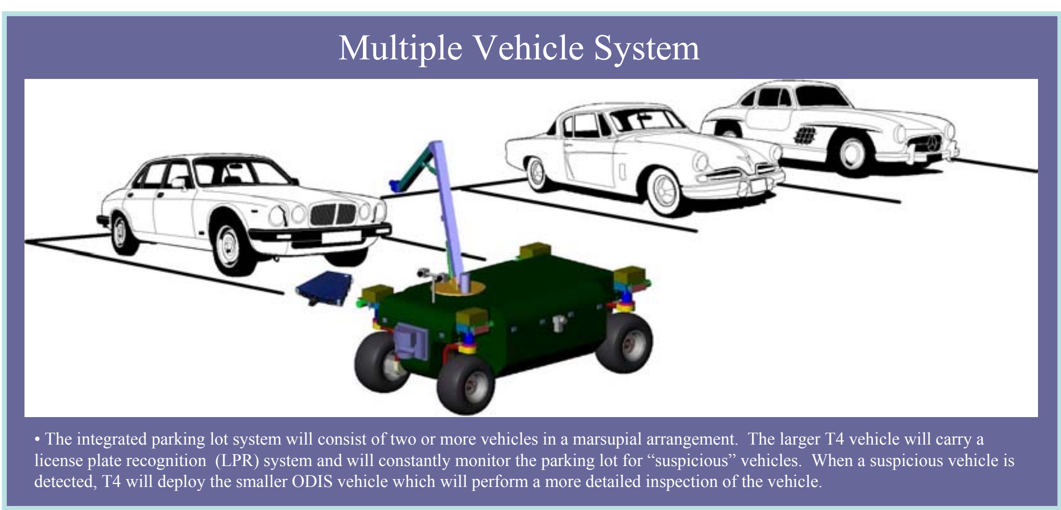


Figure 9: Integrated parking lot surveillance system.

A key feature of the system shown in Figure 9 is the T4 robot. T4 was designed to be a rugged ODV robot based on hydraulic-motor-based smart wheels and using a gasoline powered motor. The vehicle is similar in size to T2, with a weight of about 1500 lbs. Figure 10 shows T4 in its current stage of completion. This effort ended with a completely-designed and operational mechanical system and completely-design vetronics hardware. However, the pressing needs of national security re-directed CSOIS efforts toward continued ODIS development and the mechanical and vetronic subsystems of T4 were never integrated, though the long-term goal remains the same. We comment that the original development roles of the T4 project included extensive software and sensor efforts. While the hardware was under construction, the software team proceeded by outfitting the T2 robot with all the sensors planned for the T4 robot. This modified T2 was called the T2e robot (see Figure 11) and was used extensively for intelligent behavior experimentation.

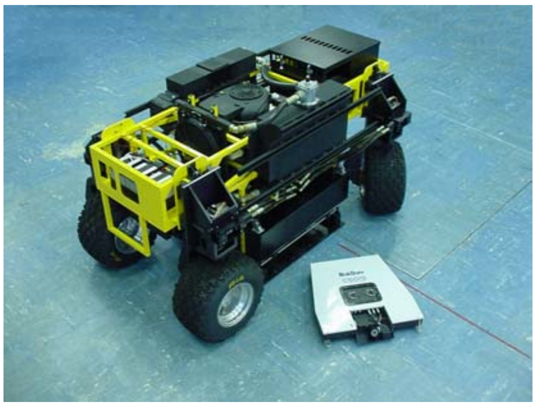


Figure 10: T4 robot.

Figure 11: T2e robot.

6. Mobility Control and Intelligent Behavior Generation

In addition to the mobility capability provided by multiple smart wheels, CSOIS has developed the vehicle electronics and planning and control systems needed to utilize the ODV capability in autonomous and semi-autonomous applications. This includes: multiple computers systems for sensing, navigation, guidance, and control; algorithms for decision-making and path tracking; user interfaces for monitoring and tasking the vehicles, and multiple sensors. Figure 12 details some of these features as found on the T2 robot, for example. Figure 13 shows the sensors on ODIS and T4.

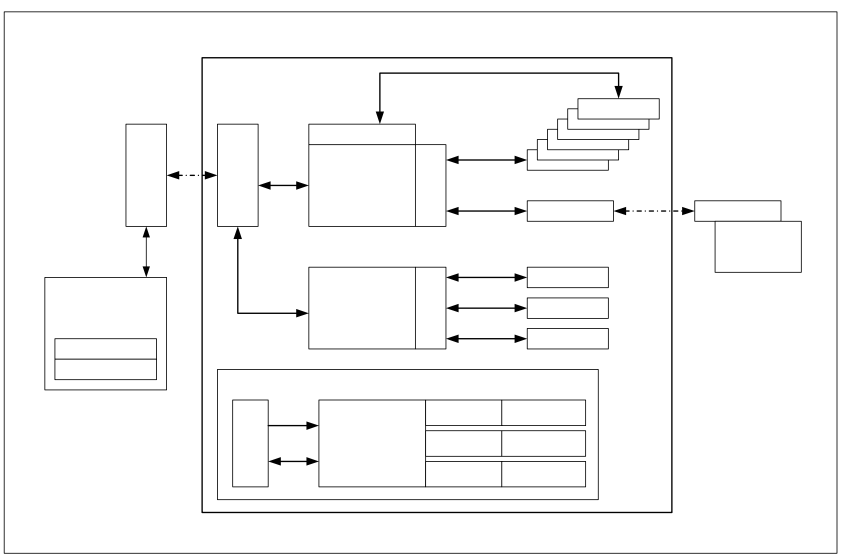


Figure 12: T2 vetronics design.

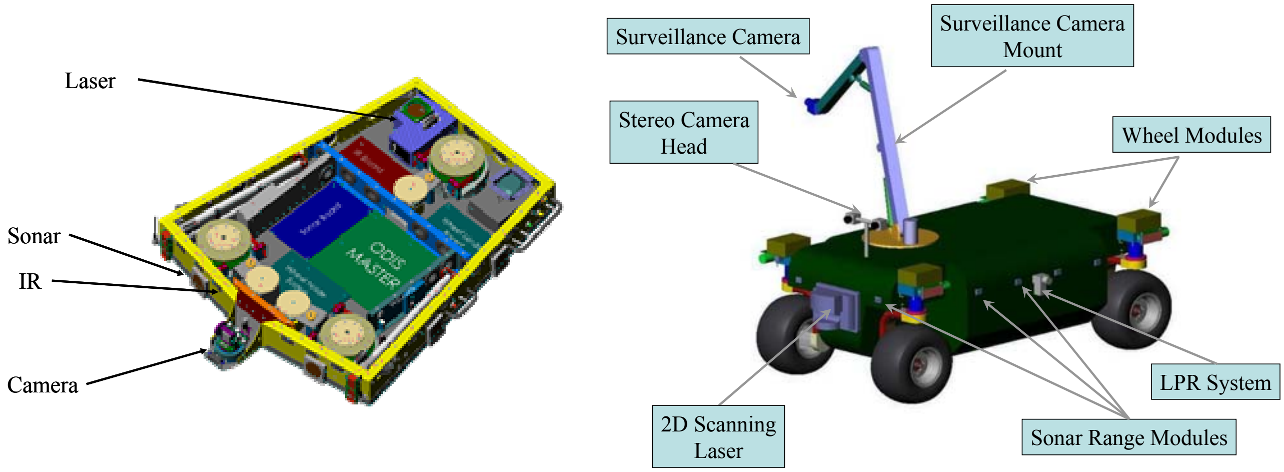


Figure 13: ODIS-I and T4/T2e sensor packs.

In addition to developing mechanical and vetronics hardware and sensors, CSOIS researchers have also done extensive work on the problem of intelligent behavior generations. For example, ODIS robots are intended to be operated in one of three different modes. In the original planned scenario, the robot should operated autonomously (ODIS-I robot). Thus, in addition to the use of smart wheels to develop the ODIS ODV mobility capability, USU designed a command environment for ODIS. Called MoRSE, an acronym for Mobile Robots in Structured Environments, the command environment provides a large number of small commands to explicitly control each system module. The command environment has been designed to implement what the USU researchers call a delayed commitment strategy. In this approach, a planner function takes as input a set of tasks and a partial map of the environment and produces from the grammar a flexible script, or sequence, of high-level action commands to be executed by the vehicle. The script is flexible in that precise paths are not specified; rather, paths are specified as functions of information to be acquired through sensing during system execution. This delayed commitment approach reduces the need to re-plan and enables vehicle behaviors to adapt to the environment. The approach includes active command of sensors and model-based interpretation of sensor data. Though currently only used on ODIS, the USU grammar-based approach to intelligent behavior generation for commanding autonomous robotic vehicles is applicable to a wide variety of autonomous systems. Note that the command environment is primarily aimed at robot-level command and control and efforts are planned to make it compatible with MHRA and JAUGS.

Due to space limitations, it is not possible to detail the various efforts carried out in the area of mobility control and intelligent behavior generation. Table I give an overall summary of these accomplishments. Interested readers are referred to the papers in the Bibliography for more details.

7. ADDITIONAL IMPACTS OF THE TACOM- USU INTELLIGENT MOBILITY PROGRAM

A common misconception about research institutions is that they are some type of "ivory tower," where faculty spend their time studying esoteric topics and publishing obtuse articles in obscure journals. And, this point of view is nothing new. The debate about the relevance of academic research has raged well over one hundred years, even leading to such (somewhat!) tongue-in-cheek comments such as those of the thermodynamicist George Francis Fitzgerald, who wrote in an 1892 letter to the journal *Nature,* that "… if Universities do not study useless subjects, who will?" However, no one will accuse CSOIS researchers of carrying out useless research. Indeed, the TACOM project is a perfect example of the research cycle, where theoretical ideas are proposed, explored, refined, and finally commercialized. The goal of the research was to develop a new generation of intelligent and highly-mobile robots. CSOIS researchers began by designing, developing, and building three prototype robotic vehicles: T1, T2, and T3, each based upon the key enabling concept of the smart Wheel. The next step for CSOIS was to design a complete robotic system for a practical, real-world application. This led to the ODIS family, which led to one of the outcomes of the TACOM project: a licensing

agreement with a manufacturing firm that will do volume production of the ODIS-T2 robot and the application of these robots for military physical security/force protection and for homeland security applications in the fight against terrorism. However, beyond commercialization, other scholarly, educational, and economic benefits of the TACOM IM Program at USU in the past six years include:

Educational

- 2 PhD students graduated with 2 others expected this year
- 38 MS and ME students graduated
- Numerous ECE and MAE Senior Design Projects

Scholarly

- Five faculty collaborating between three different departments
- Two books
- Over 100 refereed journal and conference publications
- 18 visiting research scholars from 7 countries (3 month to 1 year visits)

Economic

- 14 full-time staff employed (average of 7 FTE per year)
- 8 PhD students employed
- 64 MS and ME students employed
- 31 Undergraduate students employed
- 12 Other staff employed

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We have chosen to not refer specifically to individual reference in this paper, but to list a number of key publications related to the USU-TACOM IM program. A complete list of all publications produced under this program, including many downloadable links to these papers, can be found at http://www.csois.usu.edu/publications.

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Table 1: TACOM-USU IP Program Summary

	1998-1999	1999-2000	2000-2001 / 2001-2002 / 2002 / 2003	2002-2004
VEHICLE	T1, T2 95 lbs, 1480 lbs	T3 100 lbs	ODIS-I, ODIS-T, ODIS-S, ODIS-T2 40-50 lbs	T4, T2e 1480 lbs
CONCEPT	•Smart wheel, ODV •6 wheel, DC-motor drive/steer •Battery power •T1 in-hub power and electronics •T2 to show scalability of smart wheel	•Smart wheel, ODV •6 wheel •z-axis actuation •DC-motor drive/steer •Battery power	•ODV application - ODIS-I: full autonomy - ODIS-T: tele-op only - ODIS-S: semi-autonomous - ODIS-T2: optimized ODIS-T •Continuous vetronics improvement •DC-motor drive/steer, battery power	•T4 - Hydraulic motor drive/steer - Gasoline engine powered - Marsupial mothership for ODIS •T2e - Sensor-enriched T2 - Testbed for software development
SENSORS	•Encoders, vehicle status (T1, T2, T3, T4, ODIS-x) •Odometry (T1, T2, T3, T4, ODIS-x) •GPS/DGPS,FOG/Compass (T2, T3, ODIS-I, ODIS-S) •No payload (T1, T2, T3)		see ODIS table below	•2-D gimbaled scanning laser •Sonar ring •Stereo camera •License plate recognition camera •Surveillance camera on arm (concept) •Docking system for ODIS (concept)
COMMS VETRONICS	•Radio modem (T1, T2, T3) •Wireless LAN (T2)	•T1: 7 microcontrollers •T2: 6 microcontroller 3 Pentium-class SBC •T3: 6 microcontrollers 1 Pentium-class SBC	see ODIS table below	•Multi-processor system •Improved vetronics •Radio modem and wireless LAN
CONTROL	•Tele-operation and autonomy •Waypoint-based tracking •Temporal-based path-tracking •Primitive-based path tracking •PID motor control •Adaptive motor control	•6-DOF temporal path tracking and "MakeSetPoints" algorithm •Fuzzy-logic stair climbing •Optimal, nonlinear path-tracking control	•Epsilon-controller •Automated wheel calibration procedure •Reactive behaviors (script-based)	•Multi-sensor fusion for control •ODIS docking control (concept)
PLANNING	•A*-based path planner from waypoints •A*-based coverage planner •Graph-based planning for grammar-based control architectures •Task decomposition approach to path planning		•Command language for robotics (MoRSE) •Reactive behaviors for planning and control under uncertainty •Architecture for intelligent behavior generation •Multi-vehicle coordination	

	ODIS-I	ODIS-T	ODIS-S	ODIS-T2
•Camera	Yes	Yes	Yes	Yes
•Laser	Yes	No	Yes	No
•Sonar	10	No	2	No
•IR	32	No	8	No
•Other Payloads	No	Yes	Yes	Yes
•Radio Modem	Yes	Yes	Yes	Yes
•Wireless Lan	Yes	No	Yes	No
•Microcontroller	6	4	3	4
•Pentium-class SBC	1	0	2	0